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RESEARCH MEMORANDUM

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IV - PERFORMANCE WITH TAIL-PIPE BURNING AND WATER INJECTION

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By Robert O. Dietz, Jr., George Wishnek
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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WASHINGTON

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SUMMARY

Thrust augmentation of an axial-flow-type turbojet engine by a combination of tail-pipe burning and water injection has been investigated in the Cleveland altitude wind tunnel. Water was injected into the engine inlet and the engine combustion chambers. Performance was investigated over a range of simulated flight conditions and water injection rates while the engine was operated at rated speed and the tail-pipe fuel flow was regulated to maintain a constant turbine-outlet temperature. A constant inlet-air temperature of 520° R was maintained during water injection into the engine inlet in order to avoid icing. A fixed-area tail-pipe nozzle was used.

Thrust increases obtainable with engine-inlet water injection reached a peak at a water-air ratio of 0.035 and decreased with larger amounts of injection, whereas thrust increases obtainable with combustion-chamber water injection increased as the water-air ratio was raised throughout the range of water-air ratios investigated. For the range investigated, greater maximum thrust increases were available with combustion-chamber water injection than with engine-inlet water injection. Thrust increases obtained from either method of water injection were accompanied by large increases in specific liquid consumption.

INTRODUCTION

Augmentation of the normal thrust of turbojet engines is of importance in improving the flight characteristics of jet-propelled aircraft and in increasing the effectiveness of the turbojet engine for civilian and military applications. A general program of thrust augmentation for turbojet engines is therefore being conducted at the NACA Cleveland laboratory. Thrust augmentation of an axial-flow-type turbojet engine by burning fuel in the tail pipe is discussed in references 1 to 3. Thrust augmentation of the same turbojet engine by water injection at the compressor inlet is reported in reference 4.

The performance results of an investigation made in the Cleveland altitude wind tunnel with water injection in combination with tail-pipe burning in the following two phases are presented herein: (1) engine-inlet water injection with tail-pipe burning; and (2) combustion-chamber water injection with tail-pipe burning.

The standard tail pipe of the turbojet engine was replaced with a larger tail pipe designed to provide favorable conditions for tail-pipe burning. A fixed-area tail-pipe nozzle was used on the engine. The investigation was made over a range of flight Mach numbers at a pressure altitude of 20,000 feet and at rated engine speed. This engine speed was maintained while the water injection rate was varied over the full range obtainable with the pumping equipment. A constant turbine-outlet temperature was maintained by varying the amount of fuel burned in the tail pipe.

INSTALLATION

Engine and tail-pipe burner. - The investigation of thrust augmentation by the use of water injection in combination with tail-pipe burning was performed with an axial-flow-type 4000-pound-thrust turbojet engine having an 11-stage compressor, eight cylindrical combustion chambers, and a single-stage turbine. The standard tail pipe of the engine was replaced by a modified tail pipe, which was lengthened to include a diffuser, a combustion chamber 5 feet long and 34 inches in diameter, a reducer section, and a tail-pipe nozzle (fig. 1). Further details of the construction and performance of this tail-pipe burner are presented in reference 1. A fixed-area tail-pipe nozzle $19\frac{3}{4}$ inches in diameter was installed on the engine for the phase of the investigation in which tail-pipe burning was used. A fixed-area tail-pipe nozzle $16\frac{3}{8}$ inches in diameter was installed on the engine for the phase of the investigation in which no tail-pipe burning was used.

Water-injection equipment. - Water was injected into the engine inlet through 24 spray nozzles circumferentially installed around the inlet-air duct and flush with the duct wall. The nozzles were located at a station 6 inches upstream of the engine inlet. A
879 detailed description of this injection system and a description of the water injection nozzles are given in reference 4.

Water was injected into the combustion chambers through two nozzles in each chamber, one at the inlet and one at a station 6 inches upstream of the outlet (fig. 1). The spray nozzles at the inlet directed a conical spray upstream and were fixed to the fuel-spray nozzle supports. The nozzles near the outlet directed a conical spray normal to the gas flow into the secondary combustion zone.

Wind-tunnel installation. - The turbojet engine was supported by a wing section installed in the 20-foot-diameter test section of the altitude wind tunnel (fig. 2). Air was supplied to the engine through a duct from the tunnel make-up air system (reference 1). A labyrinth slip joint in the inlet-air duct 40 feet upstream of the engine inlet made possible the measurement of thrust with the wind-tunnel balance scale. The air was throttled from approximately sea-level pressure to the desired total pressure at the engine inlet while the pressure in the wind-tunnel test section was maintained at a value corresponding to the desired altitude.

A survey rake was mounted in the air duct about $11\frac{1}{4}$ feet upstream of the engine inlet to measure the engine air flow. Pressures and temperatures of the gases were measured at several stations in the engine (fig. 1) and thrust was determined from the wind-tunnel balance scales. The thrust and air flow were calculated by the methods presented in the appendix.

Kerosene (AN-F-32) was burned in the engine and 62-octane unleaded gasoline was burned in the tail-pipe combustion chamber.

PROCEDURE

The investigation was conducted at a pressure altitude of 20,000 feet and at flight Mach numbers from 0.26 to 0.87. At each simulated flight condition, the turbojet engine was operated at rated speed (7600 rpm). Data were obtained at various water flows while the turbine-outlet temperature was maintained at 1680° R by varying the amount of fuel burned in the tail pipe. An inlet-air temperature of about 520° R was maintained to prevent icing when water was injected into the engine inlet. Inlet-air temperatures corresponding to NACA standard altitude temperatures were maintained when water was injected into the combustion chambers. Equal amounts of water were injected at the combustion-chamber inlet and the secondary combustion zone. The total water-flow rate for either the compressor-inlet injection system or the combustion-chamber injection system was limited by the pumping equipment to a maximum of 2.65 pounds per second.

RESULTS AND DISCUSSION

Engine-inlet water injection. - The effects of water injection on engine performance with tail-pipe burning are presented in figures 3 and 4. No data points are shown on the curves inasmuch as the actual data were obtained at slightly varying turbine-outlet temperatures, which necessitated the use of cross plots to obtain the performance curves at a constant turbine-outlet temperature of 1680° R. A description of the method of cross-plotting is given in the appendix. With engine-inlet water injection in combination with tail-pipe burning on a turbojet engine, raising the water-air ratio caused an increase and a subsequent decrease in jet thrust (fig. 3(a)), net thrust (fig. 3(b)), tail-pipe fuel consumption (fig. 3(c)), total fuel consumption (fig. 3(d)), total fuel-air ratio (fig. 3(e)), and tail-pipe pressure ratio (fig. 3(f)). Thrust augmentation obtainable for the combination of engine-inlet water injection and tail-pipe burning was highest at a water-air ratio of about 0.035 (fig. 3(b)). Total liquid consumption and specific liquid consumption based on net thrust increased as the engine-inlet water injection rate was increased throughout the range of water-air ratios investigated (figs. 3(g) and 3(h), respectively). Air flow of the turbojet engine with tail-pipe burning was unaffected by engine-inlet water injection (fig. 3(i)).

Greater net thrusts (fig. 3(b)) and specific liquid consumptions based on net thrust (fig. 3(h)) were obtained with water injection at the engine inlet and tail-pipe burning than with tail-pipe burning alone. Thrust increases were larger at low flight Mach numbers than at high flight Mach numbers. Data obtained for two flight Mach numbers at a turbine-outlet temperature of 1680° R with a $19\frac{3}{4}$-inch-diameter tail-pipe nozzle are shown in the following table:

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Flight Mach number	Tail-pipe burning		Engine-inlet water injection and tail-pipe burning; water-air ratio, 0.035			
	Net thrust (lb)	Specific liquid consumption based on net thrust (lb/(hr)(lb thrust))	Net thrust (lb)	Increase in net thrust (percent)	Specific liquid consumption based on net thrust (lb/(hr)(lb thrust))	Increase in specific liquid consumption (percent)
0.26	1880	2.45	2350	25	4.27	74
.87	3620	2.16	3980	10	4.00	85

The thrust increases and specific liquid consumptions obtained with engine-inlet water injection with and without tail-pipe burning are shown in the following table. Water-injection data are presented at a water-air ratio of 0.0535 because performance data with water injection alone were available only at this value. The values were obtained with the engine operating at maximum rated conditions at a pressure altitude of 20,000 feet and a flight Mach number of about 0.26 with an inlet-air temperature of approximately 520° R.

Augmentation	Tail-pipe-nozzle diameter (in.)	Net thrust (lb)	Increase in net thrust (percent)	Specific liquid consumption based on net thrust (lb/(hr)(lb thrust))	Increase in specific liquid consumption (percent)
None	$16\frac{3}{8}$	1540		1.39	
Engine-inlet water injection; water-air ratio, 0.0535		1730	12	5.30	280
Tail-pipe burning	$19\frac{3}{4}$	1880	22	2.45	75
Engine-inlet water injection with tail-pipe burning; water-air ratio, 0.0535		2315	50	5.29	278

The values obtained without tail-pipe burning are taken from reference 4.

The increase in net thrust caused by inlet water injection and tail-pipe burning at a water-air ratio of 0.0535 over the thrust obtained with tail-pipe burning alone is 23 percent. The corresponding increase in specific liquid consumption is 116 percent.

Engine-inlet water injection is impractical under conditions at which the inlet air must be heated to prevent freezing of the injected water because the abnormal inlet-air temperature that results from such heating decreases the thrust of the engine. The addition of some freezing-point depressant to the water would eliminate the necessity of heating the inlet air. The decrease in thrust caused by raising the temperature of the inlet air tends to nullify the increase in thrust obtainable from water injection; however, worth-while gains in thrust could be realized at sea level on warm days or by injection of a nonfreezing mixture of water and alcohol.

Values taken from the curves of figure 3 are not directly comparable to values from figure 4 or from references 1 to 3, except for simulated flight conditions that involve an engine inlet-air temperature of 520° R, inasmuch as a constant inlet-air temperature of 520° R was maintained with water injection into the engine inlet. NACA standard inlet temperatures were maintained with water injection into the combustion chambers and for the data presented in references 1 to 3.

Analysis for engine-inlet water injection. - Engine-inlet water injection lowered the temperature of the air flowing through the compressor because of the evaporation of water and thereby increased the compressor Mach number. Evaporation of water in the flow passages of the compressor changed the flow conditions over the blading and thus probably affected the compressor efficiency (reference 4). An increase in gas flow through the critical flow area of the engine (turbine nozzles) as a result of inlet water injection was accompanied by an increase in compressor pressure ratio. Injection of small amounts of water at the engine inlet increased the compressor pressure ratio but did not greatly affect the efficiency therefore producing an increase in turbine-outlet total pressure. Injection of larger amounts of water at the engine inlet continued to increase the compressor pressure ratio, but apparently had an adverse effect on the compressor efficiency. The result was that at high water injection rates the turbine-outlet total pressure decreased.

Combustion-chamber water injection. - With combustion-chamber water injection in combination with tail-pipe burning, raising the water-air ratio caused an increase in jet thrust (fig. 4(a)), net thrust (fig. 4(b)), tail-pipe fuel consumption (fig. 4(c)), total fuel consumption (fig. 4(d)), total fuel-air ratio (fig. 4(e)), tail-pipe pressure ratio (fig. 4(f)), total liquid consumption (fig. 4(g)), and specific liquid and fuel consumptions based on net thrust (fig. 4(h)) throughout the range of water injection rates investigated. Air flow of the turbojet engine with tail-pipe burning was unaffected by combustion-chamber water injection (fig. 4(i)). Increases in thrust and specific liquid consumption resulting from combustion-chamber water injection at two flight Mach numbers and a turbine-outlet temperature of 1680° R are shown in the following table:

Flight Mach number	Tail-pipe burning		Combustion-chamber water injection and tail-pipe burning; water-air ratio, 0.05[a]			
	Net thrust (lb)	Specific liquid consumption based on net thrust (lb/(hr)(lb thrust))	Net thrust (lb)	Increase in net thrust (percent)	Specific liquid consumption based on net thrust (lb/(hr)(lb thrust))	Increase in specific liquid consumption (percent)
0.68	2780	2.12	3251	17	4.82	127
.81	3060	2.11	3540	16	4.76	125

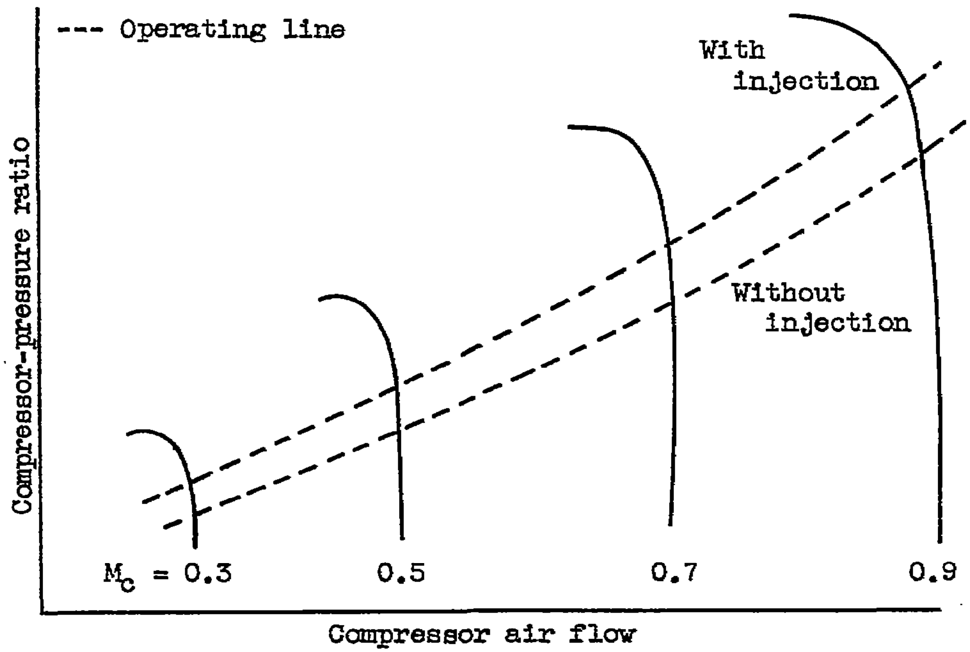
[a]Highest investigated at flight Mach number of 0.81.

A comparison of the percentage changes in the various performance parameters caused by engine-inlet water injection and combustion-chamber water injection indicates the relative merits of the two injection stations, although the difference in engine-inlet air temperatures during the two phases of the investigation places certain limitations on such a comparison. At a water-air ratio of 0.035, the rate of injection at which maximum thrust increases were available from engine-inlet water injection in combination with tail-pipe burning, greater thrust augmentation was available from engine-inlet water injection than from combustion-chamber water injection. Increases in thrust and specific liquid consumption available from the two methods of augmentation at a pressure altitude of 20,000 feet, a flight Mach number of 0.68, and a turbine-outlet temperature of 1680° R are presented in the following table:

Augmentation	Inlet-air temperature (^{o}R)	Water-air ratio	Net thrust (lb)	Increase in net thrust due to water injection (percent)	Specific liquid consumption based on net thrust (lb/(hr)(lb thrust))	Increase in specific liquid consumption due to water injection (percent)
Engine-inlet water injection with tail-pipe burning	520	0	2580	16	2.32	88
		0.035	3000		4.35	
Combustion-chamber water injection with tail-pipe burning	488	0	2780	13	2.12	94
		0.035	3130		4.11	

With the engine operating with tail-pipe burning, a greater maximum increase in net thrust was obtained with combustion-chamber water injection than with engine-inlet water. The maximum increases in net thrust obtained at a pressure altitude of 20,000 feet and a flight Mach number of about 0.68 was 17 percent from combustion-chamber injection at a water-air ratio of 0.053 (fig. 4(b)) and 16 percent from engine-inlet injection at a water-air ratio of 0.035 (fig. 3(b)). The corresponding increases in specific liquid consumption were 134 percent (fig. 4(h)) and 88 percent (fig. 3(h)), respectively. The maximum water-air ratio investigated for combustion-chamber water injection was about 0.053 and the trend of the curves indicate that still higher thrust increases could be obtained with greater injection rates (fig. 4(b)).

<u>Analysis for combustion-chamber water injection.</u> - The tail-pipe pressure ratio increased with water injection into the combustion chambers as the water-air ratio was increased throughout the range investigated (fig. 4(f)). An increase in gas flow through the critical flow area of the engine (turbine nozzles) as a result of the injection of water into the combustion chambers was accompanied by an increase in compressor-outlet pressure and a change in compressor air flow. The following chart shows typical axial-flow-compressor characteristics, with turbojet engine operating lines superimposed, for operation with and without combustion-chamber water injection:



At each flight condition, the compressor operated at a fixed Mach number; therefore, because the compressor operating line for the engine intersects the compressor Mach number curve in a region where the constant compressor Mach number curve is steep, the variation in air flow was very small. The increased pressure ratio across the compressor with practically constant air flow required a larger amount of power from the turbine. Because water injection increased the mass gas flow through the turbine and raised the specific energy content of the gases flowing through the turbine, the turbine could supply the increased power to drive the compressor with little increase in turbine pressure ratio. The turbine-outlet pressure therefore increased as the water-injection rate was increased.

Water injection gives limited gains in thrust, as can be seen from the data presented herein. These gains in thrust are accompanied by large increases in specific liquid consumption. The use of water injection to augment the thrust of a turbojet engine is therefore only practical for short periods of time.

SUMMARY OF RESULTS

From an investigation conducted in the Cleveland altitude wind tunnel of thrust augmentation of an axial-flow-type turbojet engine operating at maximum engine speed and a constant turbine-outlet temperature of 1680° R with a combination of tail-pipe burning and water injection, the following results were obtained:

1. Maximum thrust augmentation was obtained with engine-inlet water injection at a water-air ratio of about 0.035. With larger amounts of injection, augmentation decreased; whereas thrust augmentation obtainable with combustion-chamber water injection increased as the water-air ratio was raised throughout the range of water-air ratios investigated.

2. Injection of water into the engine inlet of the turbojet engine with a $19\frac{3}{4}$-inch-diameter tail-pipe nozzle operating at rated conditions with tail-pipe burning at a water-air ratio of 0.0535 produced a net thrust 23 percent greater and a specific liquid consumption 116 percent greater than the corresponding values for the engine with tail-pipe burning and no water injection. This total augmented thrust was 50 percent greater than the net thrust of the turbojet engine with a $16\frac{3}{8}$-inch-diameter nozzle and no augmentation and the specific liquid consumption was 278 percent greater. Injection of water into the inlet of the turbojet engine having a $16\frac{3}{8}$-inch-diameter tail-pipe nozzle and operating at rated conditions without tail-pipe burning at a water-air ratio of 0.0535 produced a net thrust 12 percent greater than the net thrust of the engine without water injection. This augmentation was accompanied by a 280 percent increase in specific liquid consumption.

3. At a pressure altitude of 20,000 feet and a flight Mach number of about 0.68, the maximum thrust increases for engine-inlet water injection and combustion-chamber water injection on a turbojet engine operating at rated conditions with tail-pipe burning above the thrust obtainable with tail-pipe burning alone were 16 and 17 percent, respectively. Trends of the data presented indicate that greater thrust increases could be obtained from combustion-chamber water injection at higher water-injection rates, whereas the value presented is the maximum obtainable at these inlet conditions for engine-inlet water injection.

4. Water injection gave limited gains in thrust with a large increase in specific liquid consumption; its use is therefore only practical for short periods of time.

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APPENDIX A

SYMBOLS

The following symbols are used in the analysis:

A	cross-sectional area, sq ft
B	thrust scale reading, lb
C_D	external drag coefficient of installation (determined from power-off investigations)
c_p	specific heat of gas at constant pressure, Btu/(lb)($^{\circ}$R)
F_j	jet thrust, lb
F_n	net thrust, lb
f/a	fuel-air ratio based on total fuel flow to engine and tail pipe
g	acceleration of gravity, 32.2 ft/sec^2
J	mechanical equivalent of heat, 778 ft-lb/Btu
M	Mach number
P	total pressure, lb/sq ft absolute
P_6/p_0	tail-pipe pressure ratio
p	static pressure, lb/sq ft absolute
q	dynamic pressure, lb/sq ft
R	gas constant, 53.4 ft-lb/(lb)($^{\circ}$R)
S	wing-section area, sq ft
T	total temperature, $^{\circ}$R
T_i	indicated temperature, $^{\circ}$R
t	static temperature, $^{\circ}$R

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V	velocity, ft/sec
W_a	air flow, lb/sec
W_f	total fuel consumption, lb/hr
$W_{f,t}$	tail-pipe fuel consumption, lb/hr
W_l	liquid consumption, lb/hr
W_f/F_n	specific fuel consumption based on net thrust, lb fuel/(hr)(lb thrust)
W_l/F_n	specific liquid consumption based on net thrust, lb fuel + water/(hr)(lb thrust)
w/a	water-air ratio
γ	ratio of specific heats for gases
ρ	mass density of gas, slugs/cu ft

Subscripts:

c	compressor
g	exhaust gas
j	station in exhaust jet where static pressure first reaches free-stream static pressure
r	inlet duct at survey rake, station r
x	inlet duct at slip joint, station x
0	tunnel-test-section free-air stream
1	cowl inlet
5	turbine outlet
6	tail-pipe diffuser inlet

APPENDIX B

METHODS OF CALCULATION

Temperatures

A cold calibration of a sample thermocouple up to a Mach number of about 0.8 showed that the thermocouple measured the static temperature plus approximately 85 percent of the adiabatic temperature rise owing to the impact of the air on the thermocouple. Static temperature was determined from indicated temperature by applying this factor to the adiabatic relation between temperature and pressure in the following manner: 879

$$t = \frac{T_i}{1 + 0.85\left[\left(\frac{P}{p}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]} \qquad (1)$$

The total temperature was found by use of the equation

$$T = t\left(\frac{P}{p}\right)^{\frac{\gamma-1}{\gamma}} = \frac{T_i\left(\frac{P}{p}\right)^{\frac{\gamma-1}{\gamma}}}{1 + 0.85\left[\left(\frac{P}{p}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]} \qquad (2)$$

Air Flow

The air flow through the engine was determined from pressure and temperature measurements obtained with a vertical survey rake installed in the inlet duct $11\frac{1}{4}$ feet ahead of the engine. Air flow was calculated by substituting these values of pressure and temperature in the equation

$$W_a = \rho_r A_r V_r g = \frac{p_r A_r}{R} \sqrt{\frac{2Jgc_p}{t_r}\left[\left(\frac{P_r}{p_r}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]} \qquad (3)$$

The static temperature in equation (3) was obtained by use of equation (1).

Jet Thrust

Jet thrust was determined from the balance-scale measurements by combining the forces on the installation in the following equation:

$$F_j = B + C_D q_0 S + \frac{W_a V_x}{g} + A_x (p_x - p_0) \qquad (4)$$

The second term in the right-hand side of equation (4) represents the external drag of the installation and the third and fourth terms combined represent the force on the installation at the labyrinth slipjoint in the inlet-air duct.

Equivalent Airspeed

Inasmuch as all calculations are based on 100-percent free-stream total-pressure recovery, the equivalent airspeed corresponding to the ram-pressure ratio at the engine inlet was expressed by

$$V_0 = \sqrt{2Jgc_p \quad T_1 \left[1 - \left(\frac{p_0}{P_1}\right)^{\frac{\gamma-1}{\gamma}}\right]} \qquad (5)$$

Because the adiabatic temperature rise due to the cowl-inlet velocity was low, the equivalent free-stream total temperature was assumed equal to the cowl-inlet indicated temperature. The use of this assumption introduced an error in airspeed of less than 1 percent.

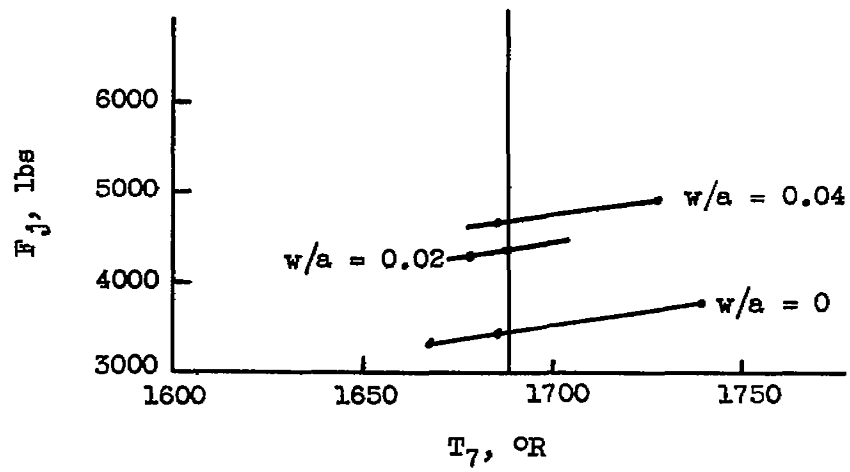
Net thrust

Net thrust was obtained by subtracting the equivalent free-stream momentum of the inlet air from the jet thrust

$$F_n = F_j - \frac{W_a V_0}{g} \tag{6}$$

Method of Cross-Plotting Data

Performance data obtained at each simulated flight condition were plotted using turbine-outlet temperature as the independent variable, as shown in the following figure:



At each simulated flight condition, data were taken at two turbine-outlet temperatures and a fixed water-air ratio in order to determine the slope of the fairings in this figure. The point at which these faired lines intersect the turbine-outlet temperature line of 1680° R gave the thrust obtainable from the system with a turbine-outlet temperature of 1680° R. Values taken from the points of intersection were then plotted in the final figures using water-air ratio as the basic parameter.

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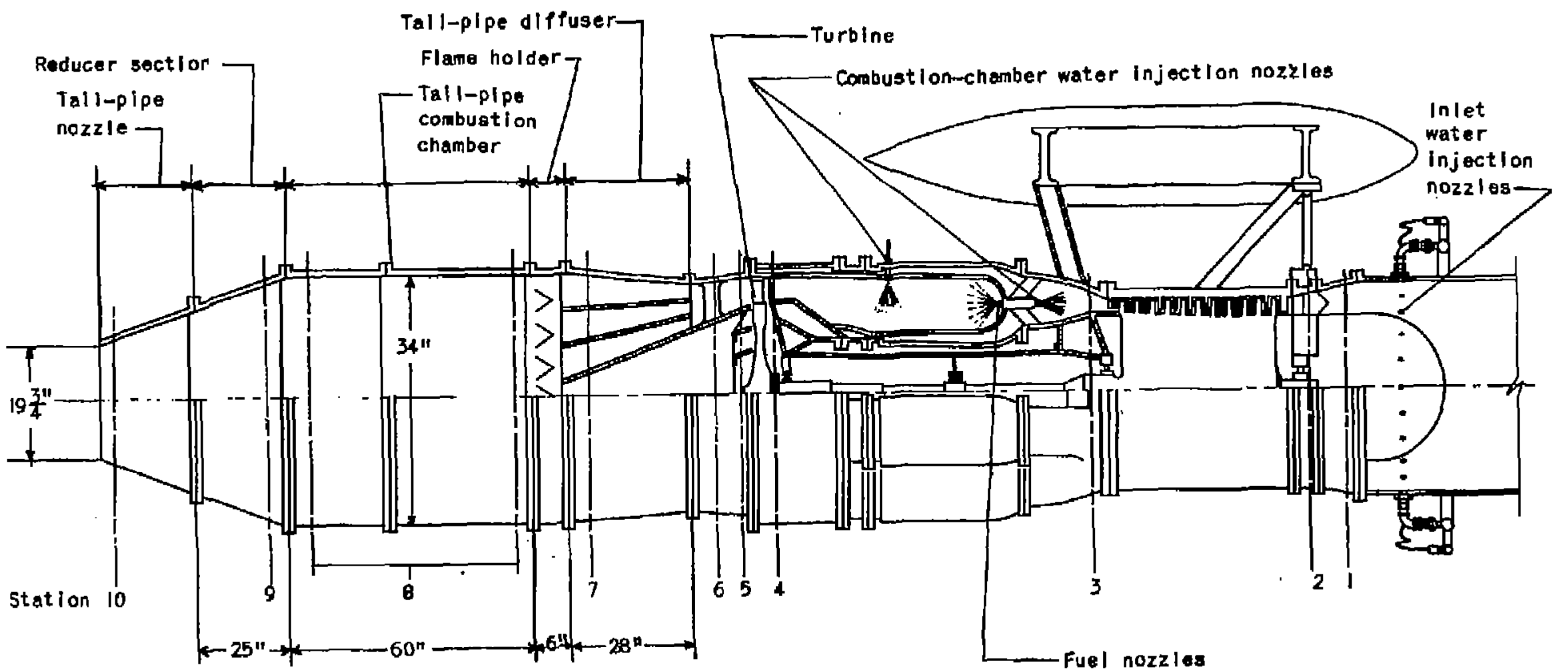

Figure 1. - Installation of turbojet engine with tail-pipe combustion chamber and water injection nozzles showing relation of component parts and measuring stations.

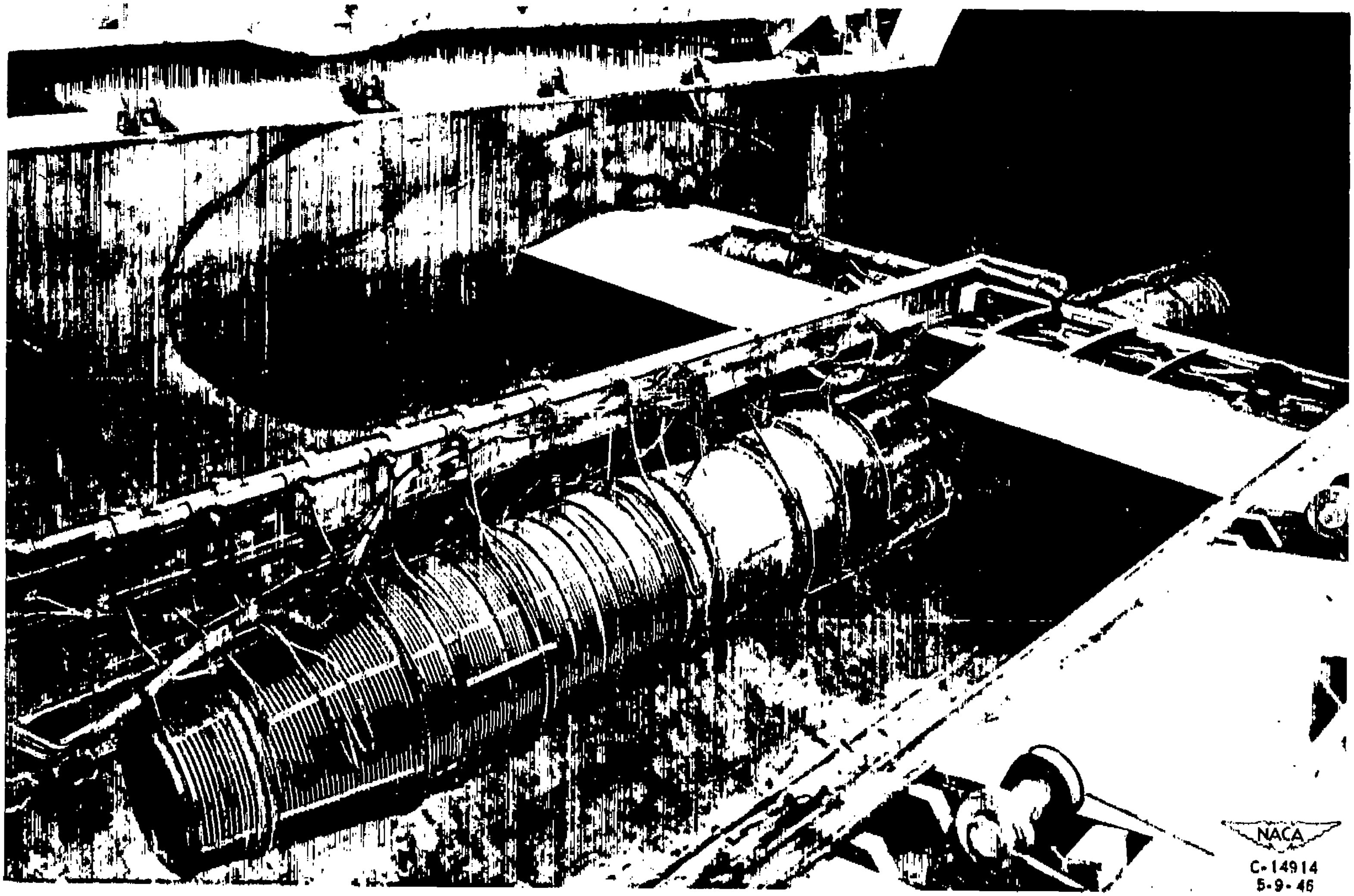

Figure 2. - Wind-tunnel installation of turbojet engine with tail-pipe combustion chamber.

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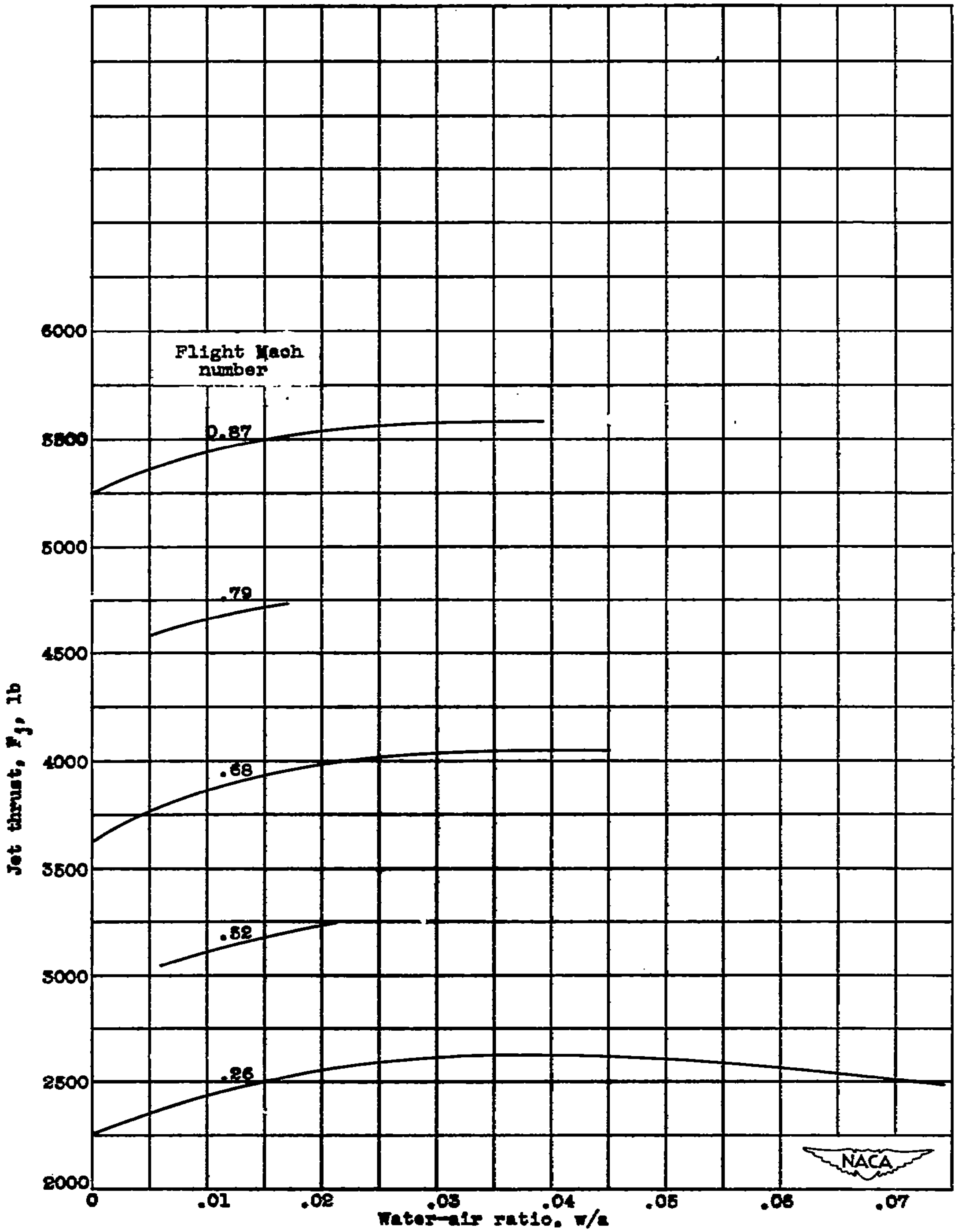

(a) Jet thrust.

Figure 3. - Effect of water injection at engine inlet on turbojet-engine performance with tail-pipe burning for several flight Mach numbers. Engine speed, 7600 rpm; pressure altitude, 20,000 feet; turbine-outlet temperature, 1680° R; engine inlet-air temperature, approximately 520° R.

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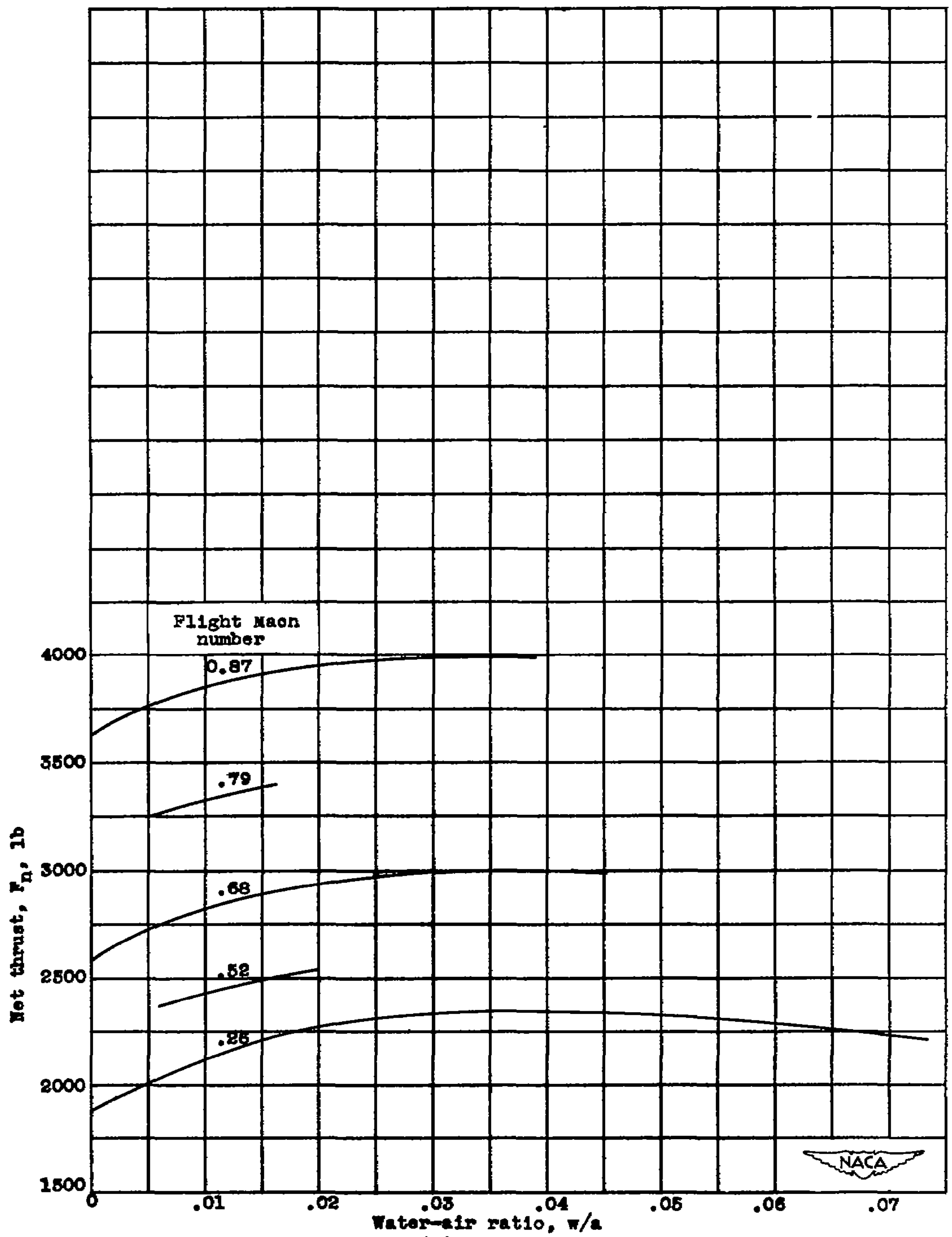

(b) Net thrust.

Figure 5. - Continued. Effect of water injection at engine inlet on turbojet-engine performance with tail-pipe burning for several flight Mach numbers. Engine speed, 7600 rpm; pressure altitude, 20,000 feet; turbine-outlet temperature, 1660° R; engine inlet-air temperature, approximately 520° R.

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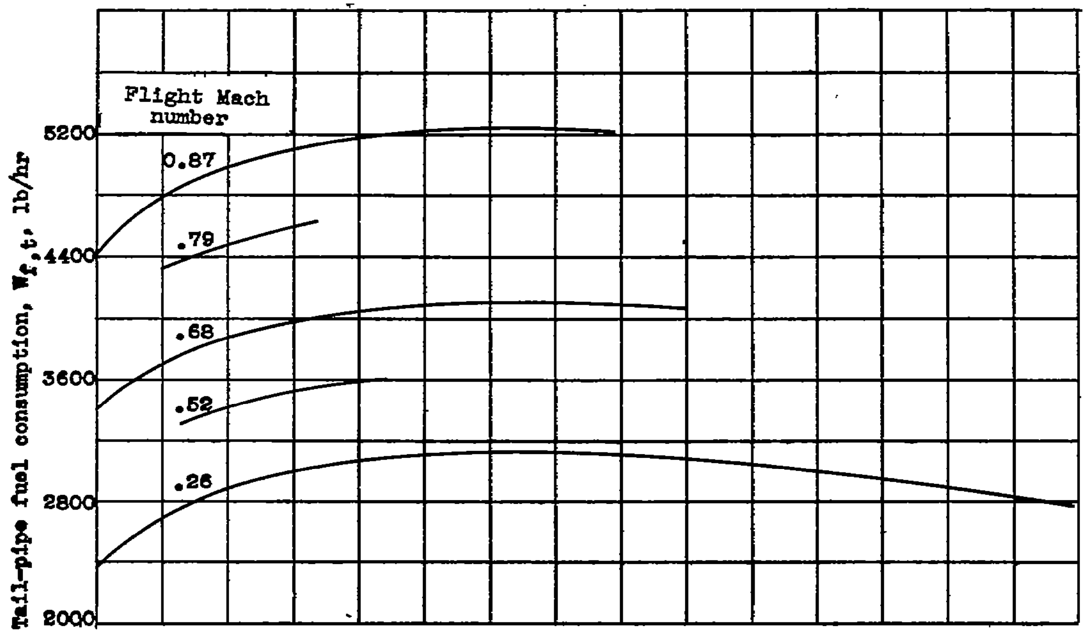
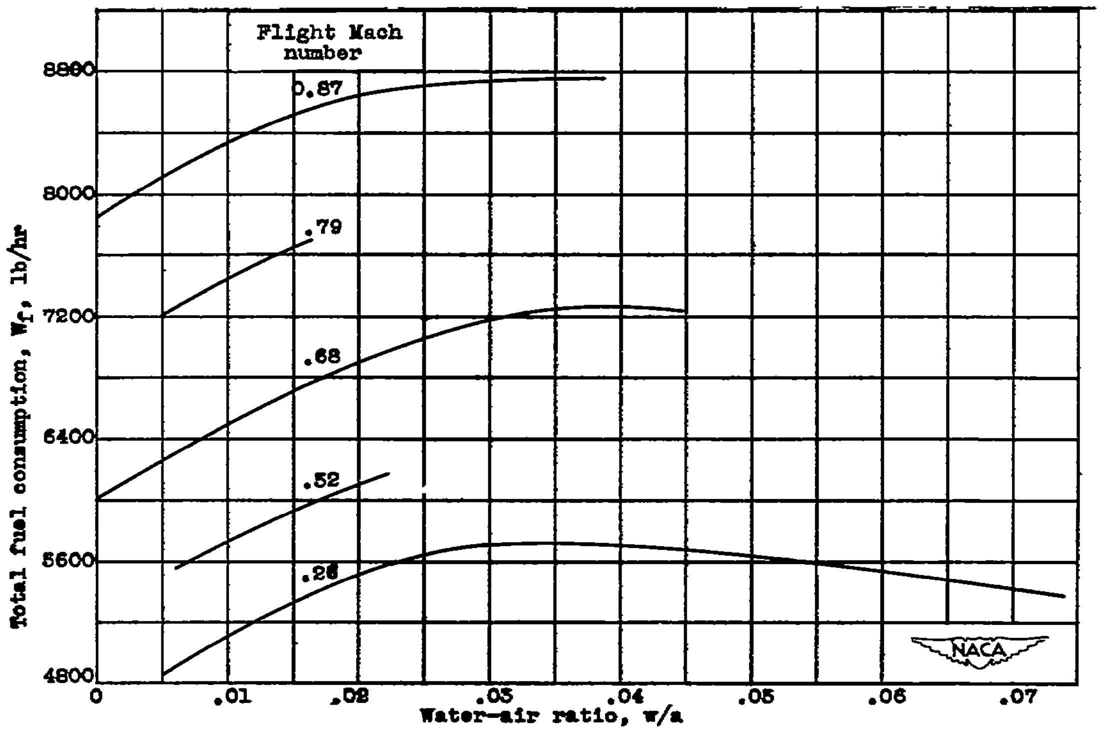
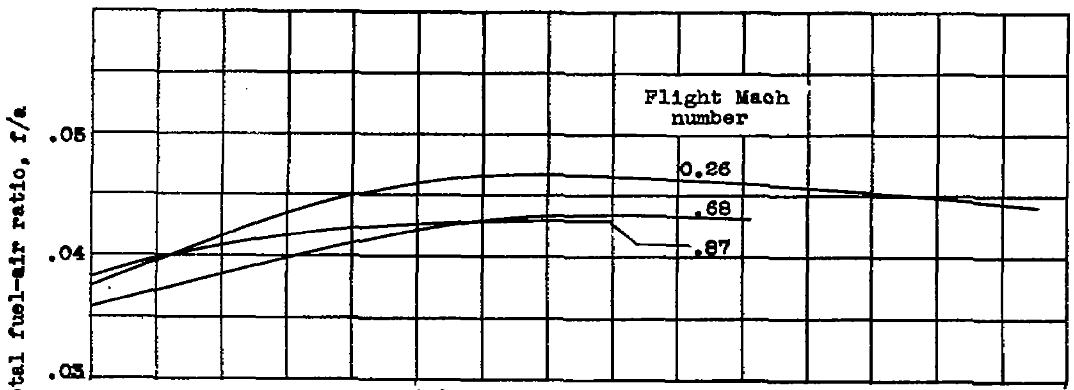


(c) Tail-pipe fuel consumption.

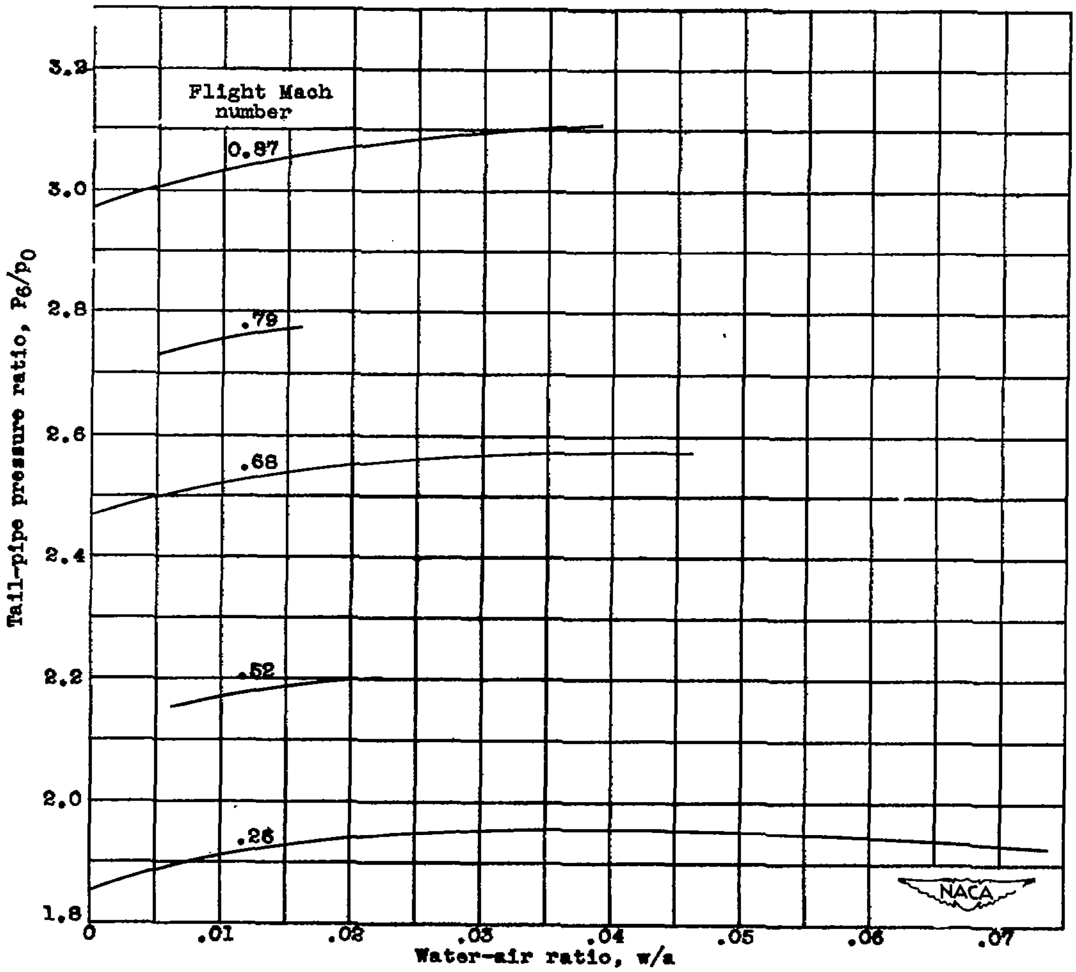


(d) Total fuel consumption.

Figure 3. - Continued. Effect of water injection at engine inlet on turbojet-engine performance with tail-pipe burning for several flight Mach numbers. Engine speed, 7600 rpm; pressure altitude, 20,000 feet; turbine-outlet temperature, 1680° R; engine inlet-air temperature, approximately 520° R.



(e) Total fuel-air ratio.



(f) Tail-pipe pressure ratio.

Figure 3. - Continued. Effect of water injection at engine inlet on turbojet-engine performance with tail-pipe burning for several flight Mach numbers. Engine speed, 7600 rpm; pressure altitude, 20,000 feet; turbine-outlet temperature, 1680° R; engine inlet-air temperature, approximately 520° R.

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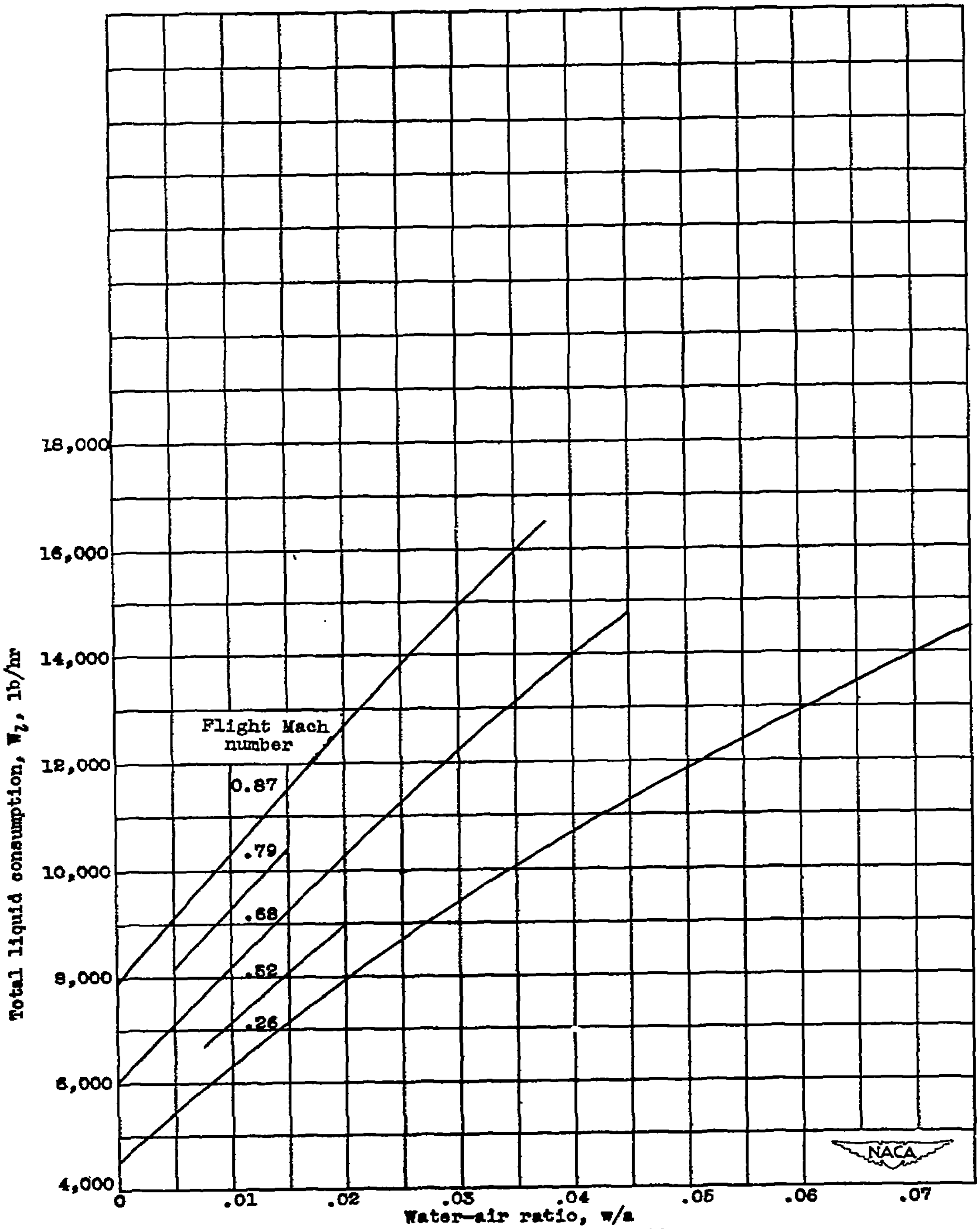

(g) Total liquid consumption.

Figure 3. - Continued. Effect of water injection at engine inlet on turbojet-engine performance with tail-pipe burning for several flight Mach numbers. Engine speed, 7600 rpm; pressure altitude, 20,000 feet; turbine-outlet temperature, 1680° R; engine inlet-air temperature, approximately 520° R.

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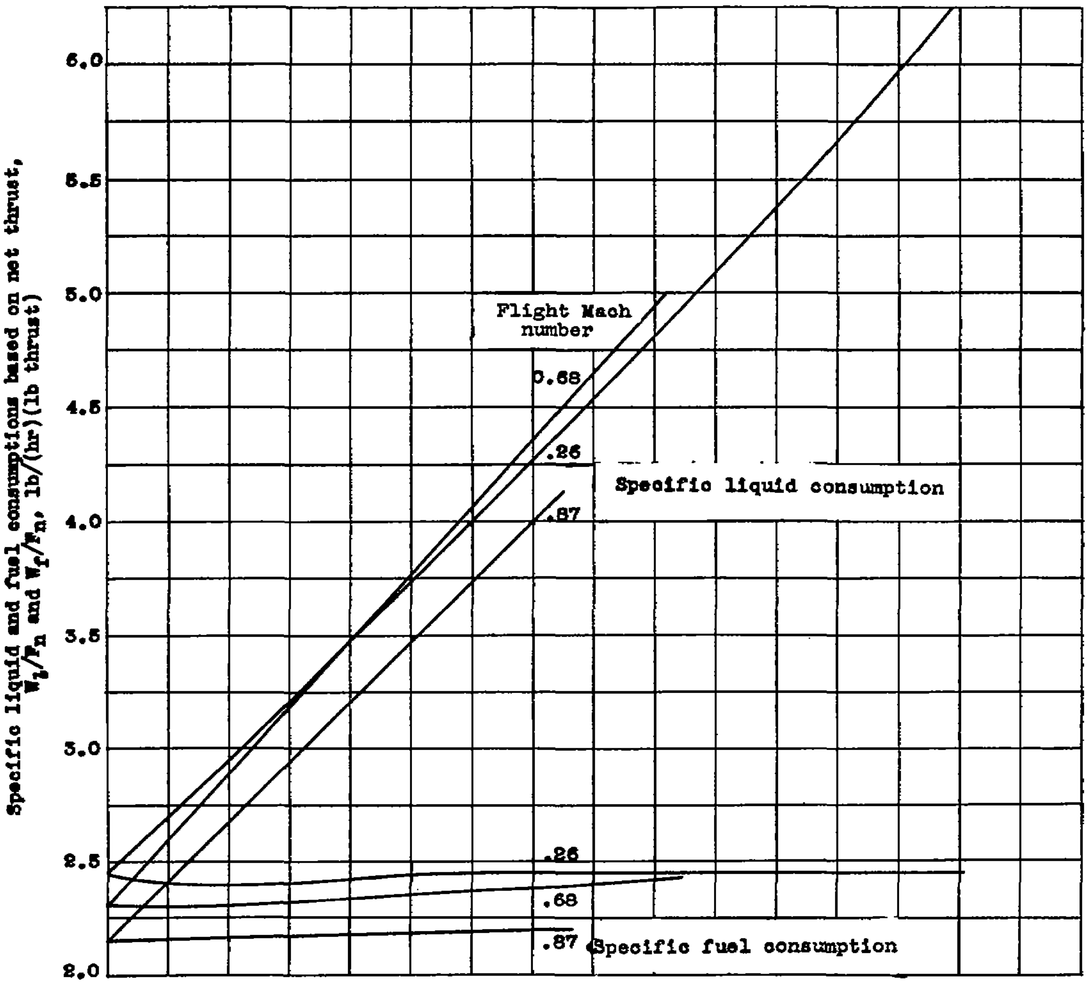
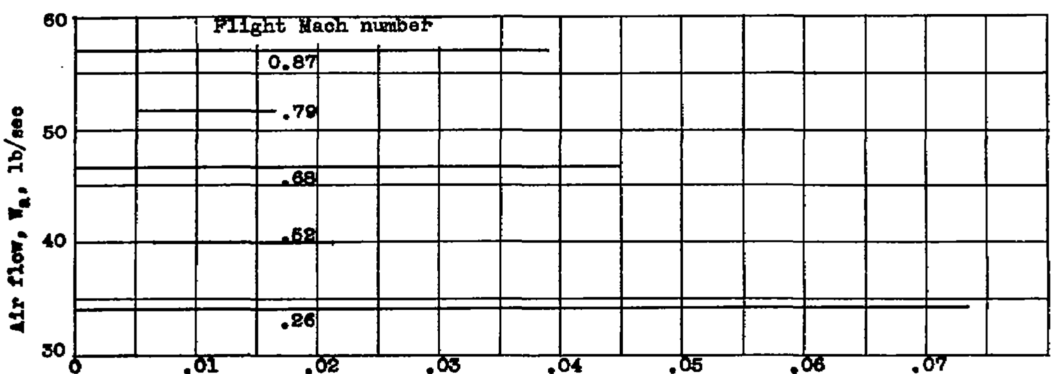


(h) Specific liquid and fuel consumptions based on net thrust.



(i) Air flow.

Figure 3. - Concluded. Effect of water injection at engine inlet on turbojet-engine performance with tail-pipe burning for several flight Mach numbers. Engine speed, 7600 rpm; pressure altitude, 20,000 feet; turbine-outlet temperature, 1680° R; engine inlet-air temperature, approximately 520° R.

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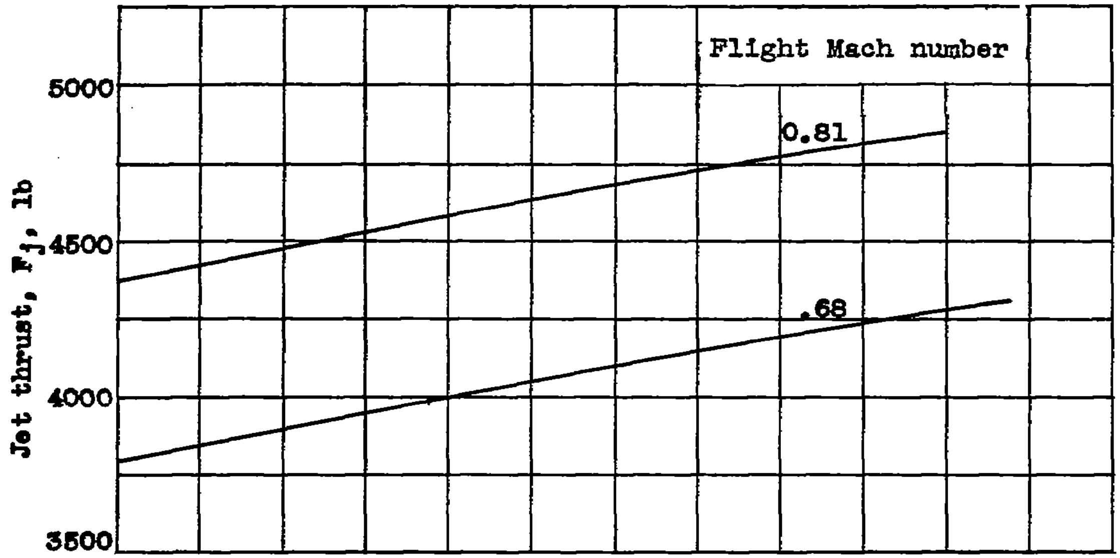
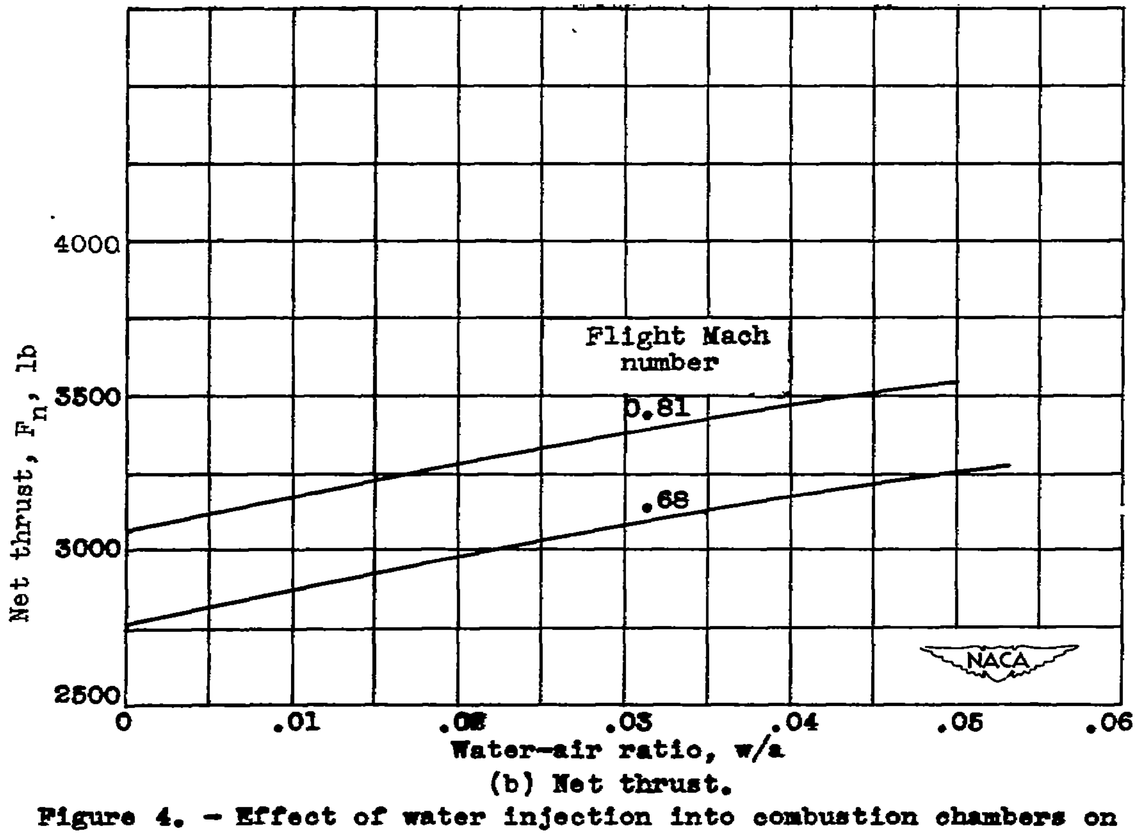
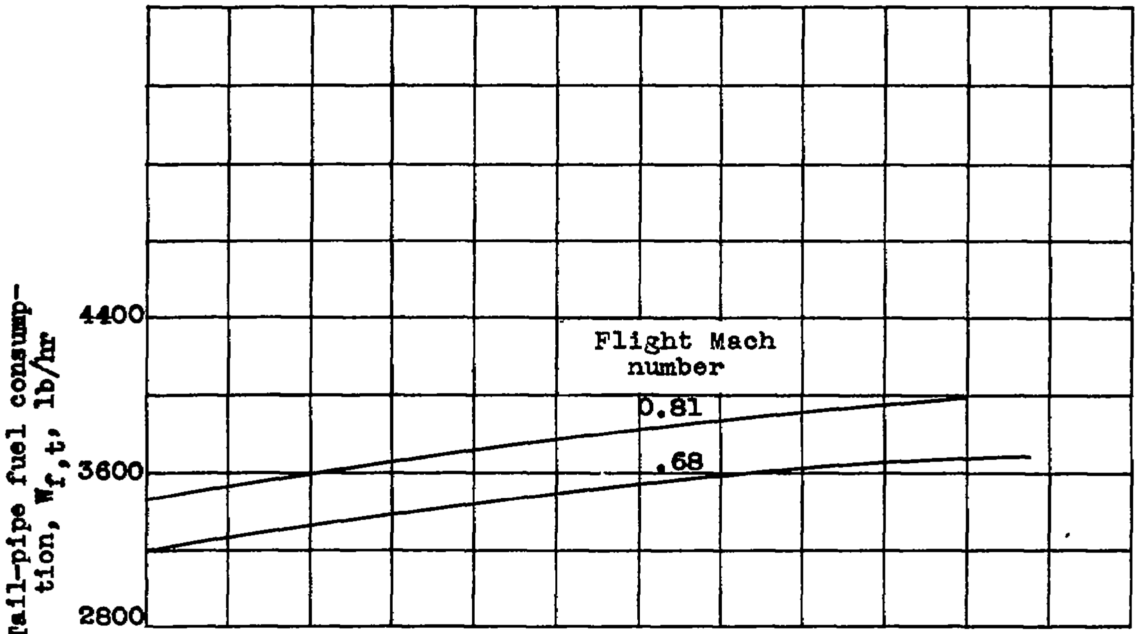


(a) Jet thrust.

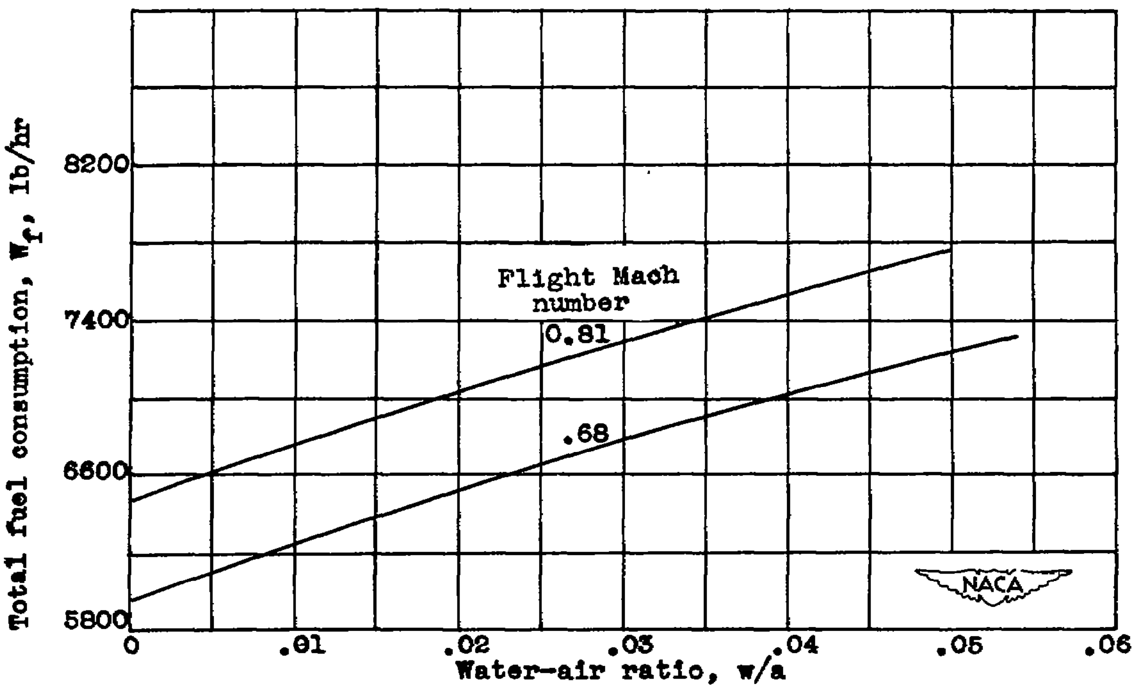


(b) Net thrust.

Figure 4. - Effect of water injection into combustion chambers on turbojet-engine-performance with tail-pipe burning for two flight Mach numbers. Engine speed, 7600 rpm; simulated altitude, 20,000 feet; turbine-outlet temperature, 1680° R.

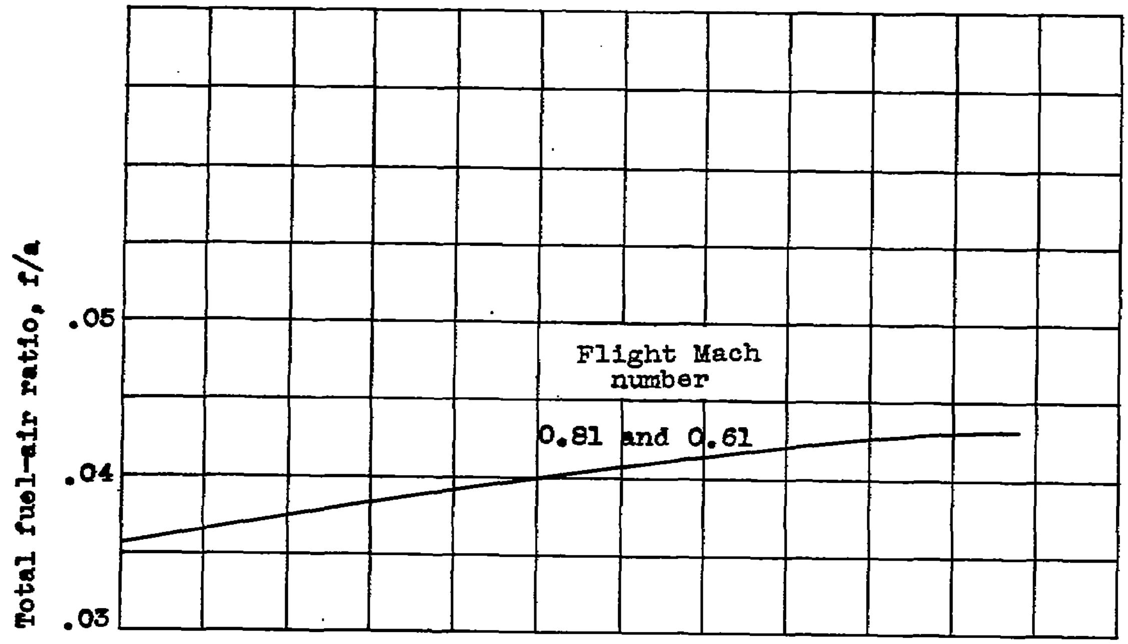


(c) Tail-pipe fuel consumption.

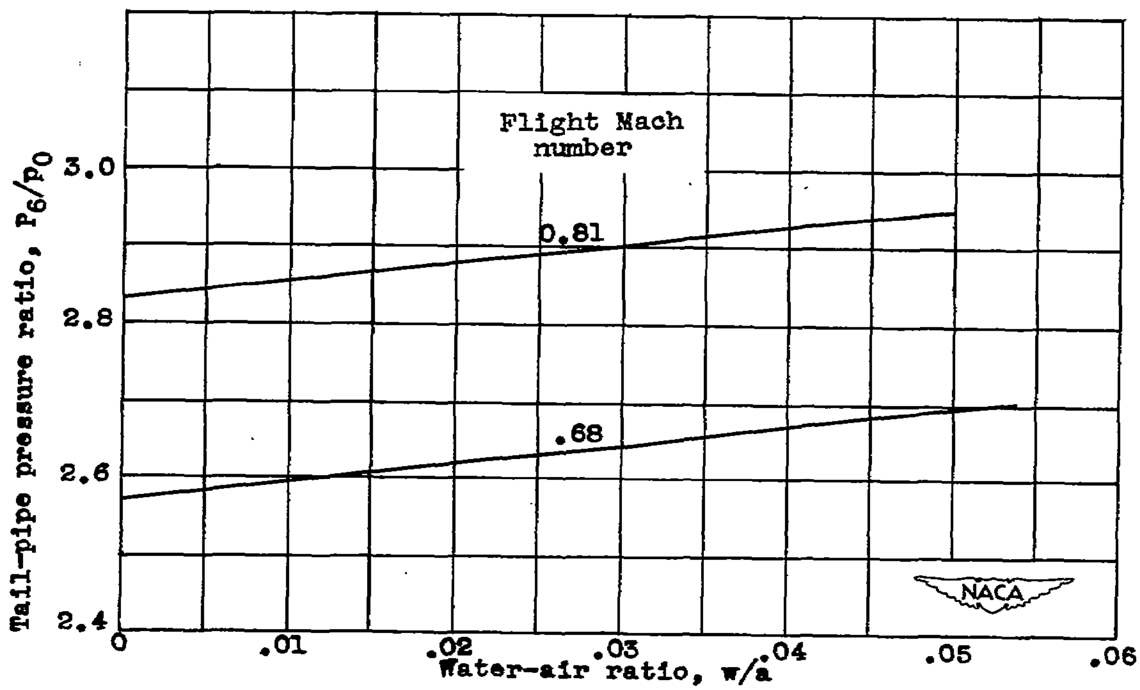


(d) Total fuel consumption.

Figure 4. - Continued. Effect of water injection into combustion chambers on turbojet-engine performance with tail-pipe burning for two flight Mach numbers. Engine speed, 7600 rpm; simulated altitude, 20,000 feet; turbine-outlet temperature, 1680° R.

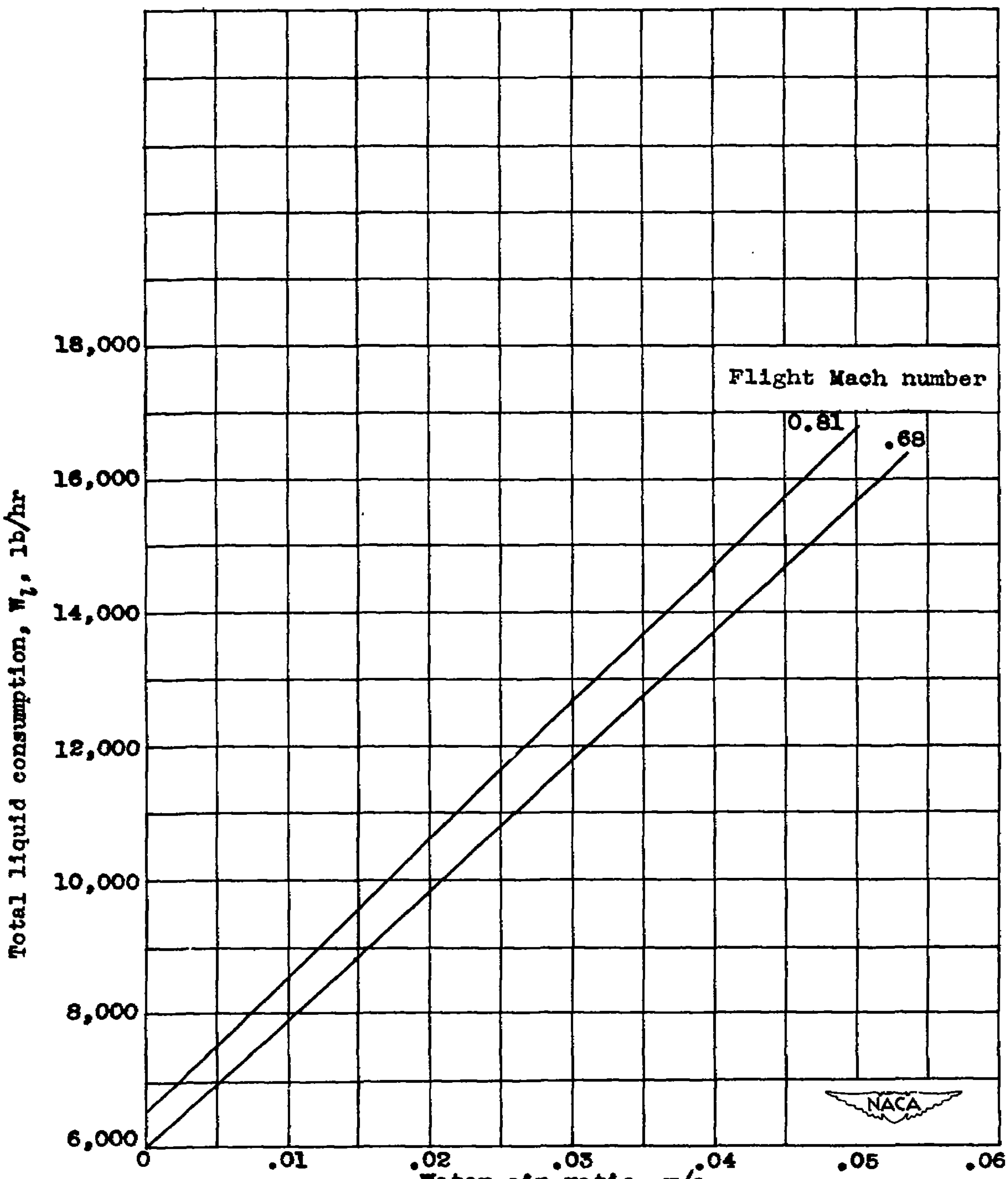


(e) Fuel-air ratio.



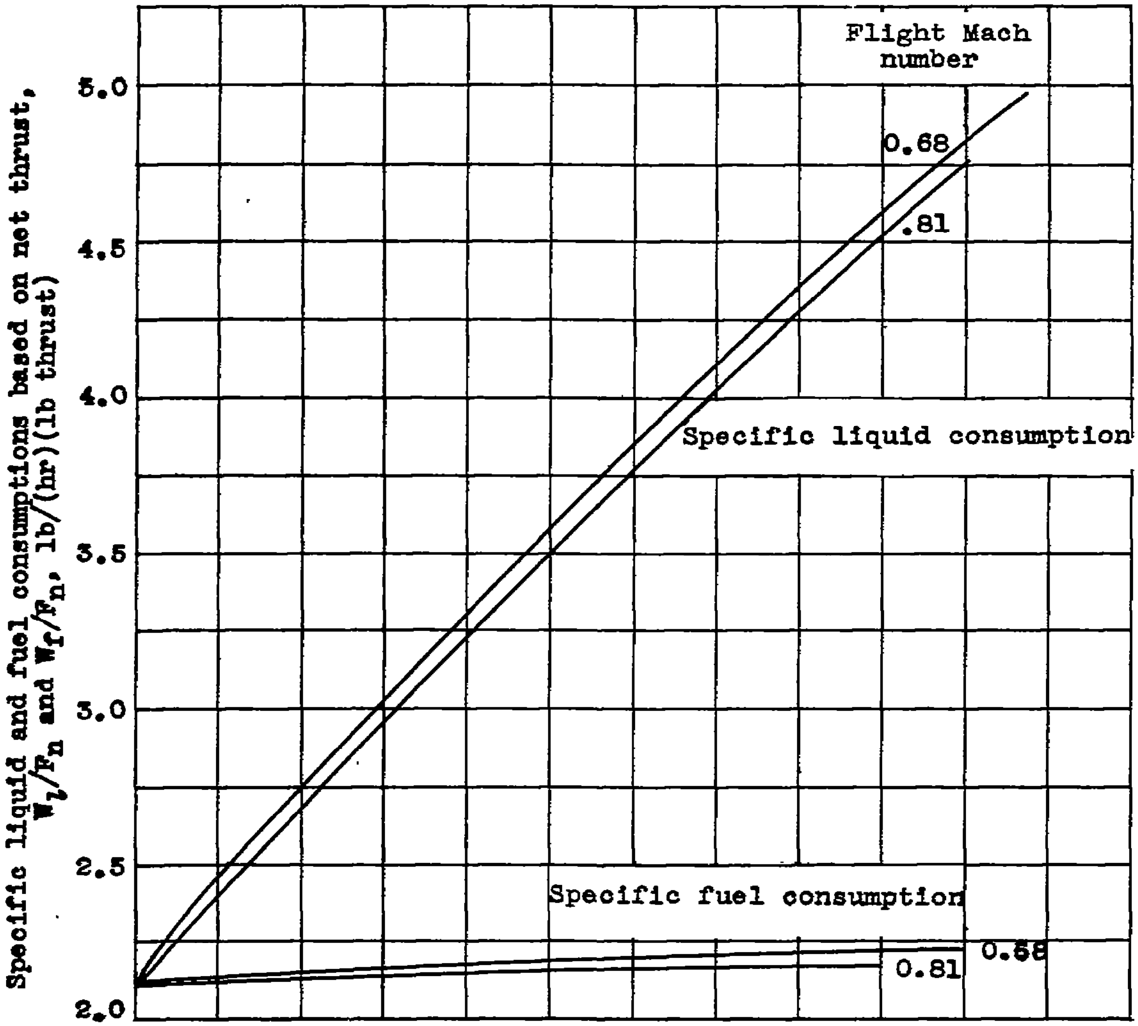
(f) Tail-pipe pressure ratio.

Figure 4. - Continued. Effect of water injection into combustion chambers on turbojet-engine performance with tail-pipe burning for two flight Mach numbers. Engine speed, 7600 rpm; simulated altitude, 20,000 feet; turbine-outlet temperature, 1680° R.

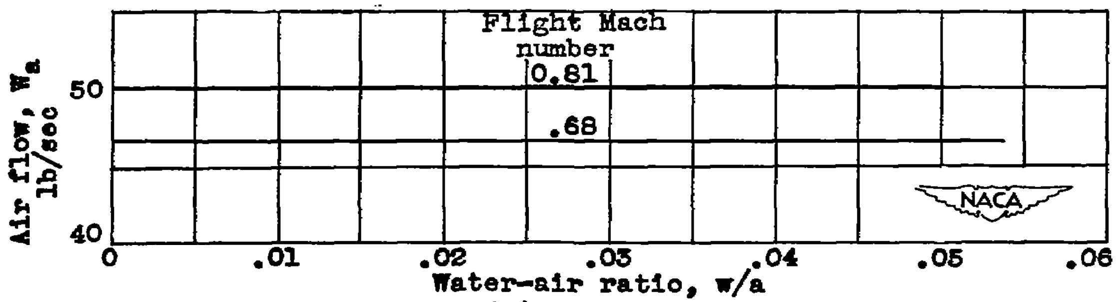


(g) Total liquid consumption.

Figure 4. - Continued. Effect of water injection into combustion chambers on turbojet-engine performance with tail-pipe burning for two flight Mach numbers. Engine speed, 7600 rpm; simulated altitude, 20,000 feet; turbine-outlet temperature, 1680° R.



(h) Specific liquid and fuel consumptions based on net thrust.



(i) Air flow.

Figure 4. - Concluded. Effect of water injection into combustion chambers on turbojet-engine performance with tail-pipe burning for two flight Mach numbers. Engine speed, 7600 rpm; simulated altitude, 20,000 feet; turbine-outlet temperature, 1680° R.